Running Head: DIFFERENCE LIMEN

Difference Limen for Dynamic Center-of-Gravity and Sinusoidal Frequency Modulated Signals

A Senior Research Thesis

Presented in partial fulfillment of the Requirements for graduation *with research distinction* in Speech and Hearing Science in the undergraduate colleges of The Ohio State University

by

Amy Stewart

The Ohio State University

Project Advisor: Lawrence L. Feth, Ph.D., Department of Speech and Hearing Science

CERTIFICATION FOR GRADUATION *WITH HONORS RESEARCH DISTINCTION*

TO: Arts and Sciences Honors Committee

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ABSTRACT

The overarching goal of this experiment was to better understand how the human central auditory system processes complex sounds. Specifically, we hypothesized that the processing of the dynamic spectral center-of-gravity (COG) of a pair of amplitude modulated (AM) tones was similar to the processing of a single tone that was sinusoidally frequency modulated (FM). The center-of-gravity effect refers to the listener's ability to track an amplitude-weighted average frequency between two tones differing in frequency by more than an octave. To create a dynamic COG, the two tones were amplitude modulated at the same modulation rate with modulators separated by a phase difference. For five normal-hearing human listeners, we used a discrimination task to determine the smallest difference in the extent of modulation that a listener can just detect. This difference, called the difference limen (DL), is thought to reflect central auditory processing. We determined these DLs across a range of center frequencies, modulation frequencies, and deviations for both FM and COG signals. We then compared the DLs of each COG signal to the DL of its *matching FM signal (*same center frequency, modulation frequency, and frequency deviation). We did not expect the DLs to be the same for FM and COG signals, but we did expect them to behave similarly as we altered their center frequencies, modulation frequencies, and frequency deviations. Analysis revealed that, even though the COG DLs were greater than the FM DLs, they generally behaved in the same way. The implication of this relationship is that it points to a physiological mechanism in the central auditory system that is able to integrate multiple sound components across a range of peripheral auditory filters.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Sound patterns that are used in everyday life, like speech or music, are complex and redundant acoustic signals. If they were not redundant and every subtle cue was imperative to the extraction of information, any slight hearing or speech impairment would be detrimental to an individual's verbal communication. So it is logical that there are mechanisms in the brain that exist to break down the complex, time-varying signals of speech and music into simpler components to extract the meaningful information. The spectral center-of-gravity (COG) effect was suggested as a mechanism that the central auditory system uses to break down complex acoustic signals so that information pertaining to frequency can be extracted.

Spectral Center-of-Gravity

The COG effect has been well-documented since the 1950's (Delattre et al., 1952). Essentially, the COG effect speaks to the human auditory system's presumed ability to track the center(s) of neural activity as a result of the spectral components of complex sounds, such as speech, or complex tones. Figure 1 shows that the COG is an amplitude-weighted average frequency between two tones. If the amplitude ratio between two fixed-frequency tones changes, the COG will "swing" toward the tone of greater amplitude.

COG in Speech

The COG effect was first reported as a static effect in speech acoustics. Delattre et al. (1952) conducted an experiment to try to create synthetic versions of the 16 cardinal vowels of the IPA. They found that they could create very realistic replications of each vowel with only two formants. A formant is a spectral peak of a spoken vowel. The finding that only two formants were necessary for recognition of a synthetic vowel spurred the idea that realistic synthetic vowels might be created with only one formant. They discovered that the vowels with naturally-occurring formants 1 and 2 relatively close together, namely the back vowels / u o ɔ ɒ ɑ a /, could be created synthetically with only one spectral peak located between the naturally-occurring formants 1 and 2. This single-formant approximation is a result of the COG effect. Presumably, the human central auditory system is able to track the spectral center of the naturally-occurring formants, so a similar perception can be created in a synthetic vowel with a single formant located at that COG.

Then, COG research turned from static to dynamic speech sounds. Lublinskaja (1997) studied the COG effect by manipulating the formants of Russian synthetic vowels. She changed the amplitudes of the second and third formants of synthetic vowels slowly over time to determine how the perception of the vowels would change. She found that the perception of these synthetic vowels was very similar to the perception of diphthongs. A diphthong is a vowel that slowly shifts in formant frequencies. This study demonstrated that a frequency shift can be simulated by manipulating the relative amplitudes of surrounding frequencies. It was a landmark study because it was the first to demonstrate how the COG effect functions dynamically.

Research in the COG effect in speech signals then turned from vowels alone to consonant-vowel (CV) transitions. Feth et al. (2004) used two kinds of synthetic CV transitions. Frequency-modulated (FM) CV transitions were created by directly changing the frequency of the signal over time. Virtual frequency (VF) CV transitions were created by co-varying the amplitudes of two component frequencies over time. (The amplitude of one component frequency was increased while the amplitude of the other component frequency was decreased so the COG of the component frequencies shifted.) They conducted an experiment to see if FM and VF CV transitions were processed similarly to synthetic format transitions. They found that, regardless of the stimulus type, a person could discriminate between two consonant-vowel pairs as long as the third formant was changing the correct way. This means that the VF, FM, and synthetic formant transitions were probably processed similarly.

COG in Tones

Study of the COG effect spread into psychoacoustics so the complexity of the sound signals could be reduced further into tones. Rather inadvertently, Wakefield and Edwards (1988) were the first to record the COG effect in tones. They were studying the sensitivity of the human auditory system to phase differences between two fixed-frequency AM tones to see if listeners were sensitive to modulation phase difference across auditory filters. They found that listeners were able to distinguish two-tone complex signals that differed only in the phase relationship between their modulations, even when the component tones were separated by a large frequency span. This gives us another glimpse into the COG effect. What seems like spectral integration across a broad frequency spectrum demonstrates the human auditory system's ability to simultaneously process sounds outside of one auditory filter. There must be some central auditory processor integrating these sounds.

Dawson and Feth (2004) conducted an experiment with FM and VF glides. Similar to an FM CV transition, an FM glide is created simply by slowly raising or lowering the frequency of a tone over time. Similar to a VF CV transition, a VF glide is created with two fixed-frequency tones. One of the tones starts with a low amplitude and slowly increases. The other tone starts with a high amplitude and slowly decreases. Listeners were asked to determine the direction of both FM and VF glides. They found that the patterns of behavior for VF glides were similar to the patterns of behavior for FM glides. This indicates similar processing of FM and VF glides.

Anantharaman (1998) created a mathematical model for the COG effect. (He referred to it as the “spectral centroid.”) To gather more data about the processing of dynamic COG signals, he experimented with VF glides. Listeners were asked to match the rate of frequency change in VF glides to the change in FM glides. Anantharaman found that listeners were nearly as good at matching VF glides to FM glides as they were at matching FM glides to other FM glides. This provided further evidence for dynamic COG signals being processed similarly to FM signals. However, there was a possibility that listeners were paying attention to the amplitude directionality of only one component of the signals instead of integrating both frequency components. The study was modified to rule out this possibility by using periodically dynamic signals only different in the phase relationship of the modulators.

Hudson et al. (2009) were the first to use these periodic, dynamic signals for the purpose of studying the COG effect. (Wakefield and Edwards (1988) used the same kind of signals to study phase sensitivity.) Two types of sound signals were utilized: dynamic COG signals and sinusoidal FM signals. To create a dynamic COG, the two tones were amplitude modulated at the same rate, but the modulators were separated by a phase difference. To create a sinusoidal FM, the frequency of a fixed-amplitude tone was varied by a low-frequency sinusoid. They used the DL as a measurement to reflect central auditory processing. For this study, a DL measured the smallest change in the extent of modulation that a listener can just detect. They found FM and COG DLs across a range of center frequencies (CFs), modulation frequencies (MFs), deviations from center frequency (Devs), and spectral separations between component frequencies of the COG signals. Results of the study were inconclusive, but generally support the idea that listeners can detect the dynamic COG signals similarly to the FM signals.

FM Signals

The sinusoidal FM signal refers to a single pure tone that is sinusoidally frequency-modulated. FM signals are identified by their center frequencies, modulation frequencies, and deviation from center frequency. The auditory processing of sinusoidal FM signals has been well-documented so it will serve as a reference for investigation of the COG signals for the current study.

Ozimek and Sek’s (1990) study was instrumental in determining how FM tones are being processed by the central auditory system. They used a same-different task to find DLs for FM signals across a range of center frequencies (CF: 250, 500, and 1000 Hz), modulation frequencies (MF: 2, 8, 32, and 128 Hz), and deviations (Dev: 6, 12, 25, and 50 Hz). As illustrated in their Figure 2, they found that the FM DLs remained relatively flat across a wide range of modulation rates. This means that FM DLs are independent of the modulating frequency. As demonstrated in their Figure 5, they also found that FM DLs were relatively flat across center frequencies. This means that FM DLs are independent of center frequency. Additionally, exemplified by their Figure 4, they found that FM DLs increased with increasing deviation. This means that FM DLs are at least partially dependent on deviation. These three results are important indicators of how FM signals are processed in the central auditory system. Part of the current project is to replicate these results of Ozimek and Sek's study to obtain reference DLs to compare with the experimental COG DLs.

Current Study

Purpose

The purpose of the current project is to better understand how the central auditory mechanism reduces spectral complexity especially with regard to the processing of periodically dynamic complex sounds. To accomplish this, two types of sound signals were utilized: dynamic COG signals and sinusoidal FM signals. The signals were used to find DLs. The patterns of the DLs are a good reflection of auditory processing. This is because they behaviorally measure how far a modulated tone moves across a presumed tonotopic neural network. There are two questions being investigated: 1) Can a listener detect the dynamic COG in the two-tone signals? 2) If so, are the COG signals being processed the same way as the FM signals?

Implications

The results of this project could have multiple applications. Due to the close relation of the COG effect and vowel formants, this project could change the way we look at speech intelligibility. Instead of trying to analyze natural speech or create synthetic speech based on multi-formant vowels, we could focus on a single vowel formant located at the COG of the other formants. This would only be effective, however if all the component formants are located within 5 auditory filters (or ERB), which has been found to be the limit of the COG effect.

The results of this project could also apply to hearing acuity. Highly skilled listeners, like military sonar operators, are incredibly adept at identifying sources of sound outside of the speech band that are seemingly indistinguishable for a “normal” listener. By learning more about how the human auditory system processes complex sounds within the speech band, we might be able to learn how the human auditory system processes complex sounds outside the speech band.

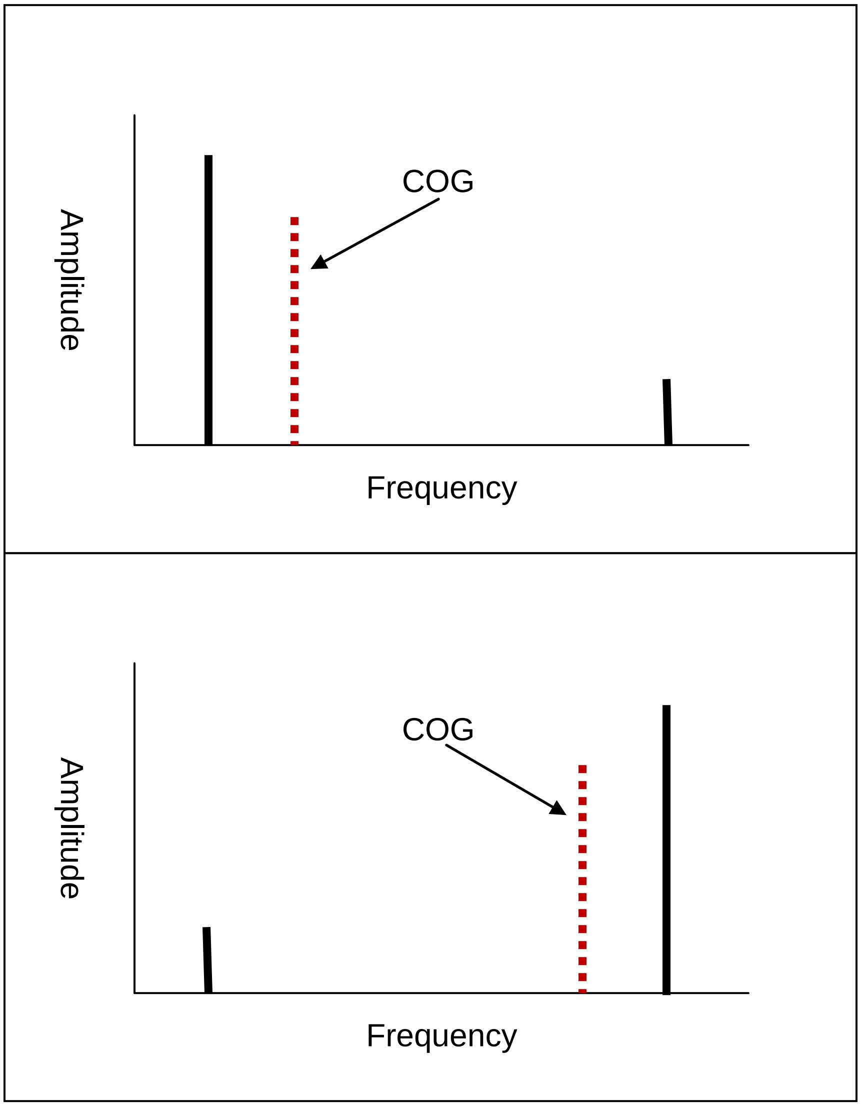

Figure 1: Schematic representation of the COG effect. COG shifts as relative amplitudes of component frequencies change.

CHAPTER 2

METHODS AND MATERIALS

Stimuli

The two types of stimuli used for the experiment were sinusoidal FM signals and dynamic COG signals. The FM signals were chosen to partially replicate Ozimek and Sek's study (1990). Three center frequencies within the speech band were utilized: 250 Hz, 500 Hz, and 1000 Hz. For each center frequency, the signals were frequency-modulated at three different rates: 4 Hz, 8 Hz, and 16 Hz. These modulation rates fall within Ozimek and Sek's (1990) "follow-up" range. They are slow enough that a listener can track the entire signal as it continuously changes frequency. For each modulation rate, four deviations were utilized: 6 Hz, 12 Hz, 25 Hz, and 50 Hz. Deviation is a measure of the difference between the maximum (highest) frequency of the modulated signal and its center frequency.

For each FM signal, an analogous COG signal was used. The COG signals were generated from two component tones that were spaced 4 ERB apart. An ERB is an equivalent rectangular bandwidth or a measurement representing the bandwidth of one auditory filter. The COG component tones were spaced 4 ERB apart which means that there were two whole auditory filters between them. The component frequencies were amplitude modulated at the same rate and with the same modulation index, but separated by a phase shift. The magnitude of the phase shift of the modulators was directly proportional to the perceived deviation.

The COG signals were matched to each FM signal using a Matlab program that calculates the dynamic COG of both FM and COG signals. The program calculated the dynamic COG of FM signals by using the unique CF, MF, and Dev. That calculation could be used to find the peak (highest) frequency of the FM signal. The two components of the COG signal were set at the same CF and MF. To match Dev, the modulators were set at a relative phase difference of 45 degrees. Then, through trial and error, the depth of amplitude modulation, reflected quantitatively through a ratio between maximum and minimum amplitude called modulation index, was adjusted until the calculated COG maximum frequency matched the calculated FM maximum frequency. This procedure was repeated for each parameter.

Subjects

Subjects for the experiment were five normal hearing young adults (ages 18-24 years, 1 male and 4 female). Signals were presented monaurally (for 4 listeners, the signals were presented to their right ears and for 1 listener, the signals were presented to his/her left ear) through calibrated Sennheiser HD 250 headphones. For three subjects, the signals were presented at a level 90 dB SPL and for two subjects, the signals were presented at a level of 70 dB SPL. The discrepancy in presentation level was due to a misadjusted RME setting in one of the sound-attenuating booths. On average, each subject listened for a total of 35 to 55 hours in 2-hour sessions. Approximately, 5 to 20 of each subject’s total hours were spent learning the tasks. The remaining time was spent collecting data. The subjects were monetarily compensated 7 to 10 dollars an hour (depending on listening experience) for their participation.

Procedures

The listeners were placed individually in the sound-attenuating booths. They were asked to view the flat computer screen in front of them and respond using a mouse. The signals were generated using custom-written Matlab programs. The sounds that were presented to the listeners were sinusoidal FM signals and analogous dynamic COG signals. Each COG signal followed the same frequency trajectory as a matching FM signal. Multiple CFs (250 Hz, 500 Hz, and 1000 Hz), MFs (4 Hz, 8 Hz, and 16 Hz), and Devs (6, 12, 25, and 50 Hz) were used for each FM-COG signal pair to determine difference limens (DLs) within the speech band (100-5000 Hz).

For this project, two signals (both either dynamic COG or sinusoidal FM) were presented to a listener. The signals only differed in Dev. The listener was asked which signal was the target signal. For FM signals, the Dev of the target signal had a Dev two times larger than the Dev of the reference signal. For instance, if the Dev of the reference signal was 25 Hz, the beginning target signal would have a Dev of 50 Hz. Figure 2 is an example of a reference signal with a Dev of 50. In this case, the starting target signal, as demonstrated by Figure 3, would have a Dev of 100 Hz. The Dev of the COG was measured in phase difference between the modulators. The phase difference between the modulators of the reference signal was calculated to create equivalent deviations of 6, 12, 25, and 50 Hz. The phase difference between the modulators of the target signal began at 45 degrees greater than the reference signals. For example, a COG reference signal with a CF of 500 Hz, MF of 4 Hz, and a Dev of 50 Hz would have a modulation index of .7 and a modulator phase difference of 45 degrees. A graphical representation of this signal is demonstrated in Figure 4. The target signal of the same CF and MF would have a modulator phase difference of 90 degrees. The equivalent Dev of this signal would be around 83 Hz. The target COG signal for this parameter was illustrated in Figure 5. However, the phase difference represented in Figure 5 was exaggerated to 150 degrees (100 Hz) so the phase difference would be more obvious.

The difference of Dev between the target and reference signals for both FM and COG signals were systematically lowered using a Levitt “3 up, 1 down” adaptive procedure (1971). To adjust the deviations of the COG signals, after the depth of amplitude modulation was set, phase difference between the modulators was changed. If the phase difference between the modulators was 180 degrees, the deviation was at a maximum. If the phase difference between the modulators was 0 degrees, there was no deviation. The DLs were defined as the smallest change in extent of modulation that a listener can detect 79.4 percent of the time. For each condition, listeners had to attain 3 FM DLs within 5 dB and 3 COG DLs within 5 degrees. FM DLs were obtained and compiled for all five subjects at CFs of 250, 500, and 1000 Hz, MFs of 4, 8, and 16 Hz, and Devs of 6, 12, 25, and 50 Hz. Subjects completed all parameters for the FM task before they began the COG task. COG DLs were obtained and compiled for all five subjects at CFs of 250, 500, and 1000 Hz, MFs of 4, 8, and 16 Hz, and Devs of 12, 25, and 50 Hz. COG DLs were unable to be obtained at Dev of 6 Hz. Listeners reported extreme difficulty in detecting any difference between the target and reference signal at a Dev of 6 Hz because the amplitude flutter of the modulators masked the very subtle shift in COG. COG DLs were measured in degrees. Using the Matlab COG calculator, each COG DL was converted back into Hz. Finally, geometric means for each condition were calculated across subjects. Geometric means are calculated by multiplying *n* numbers, then taking the *n*th root of the product. Geometric means were used because frequency is represented logarithmically in the auditory system.

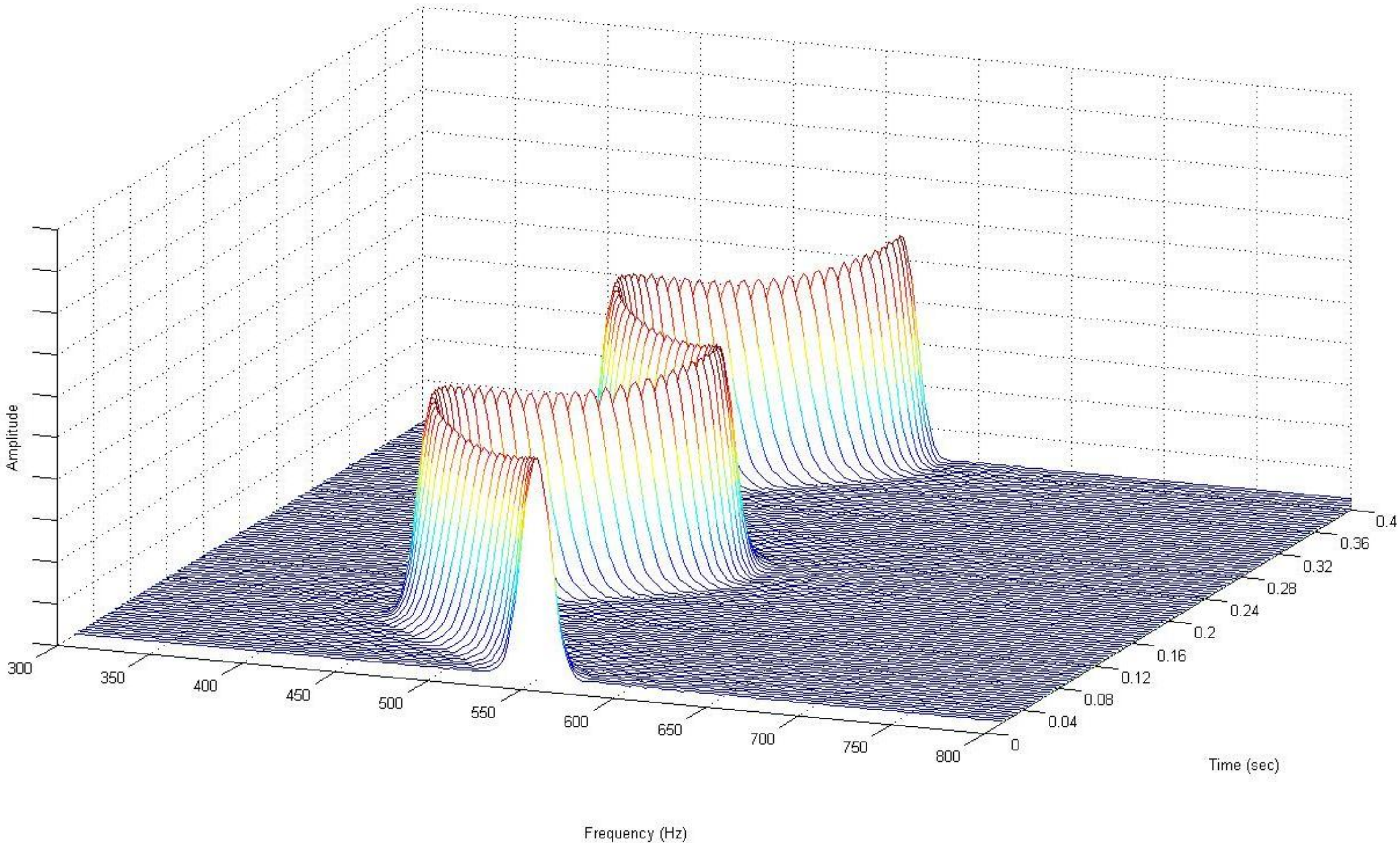

Figure 2: Spectral representation of a frequency-modulated fixed-amplitude tone with CF: 500 Hz, MF: 4 Hz, and Dev: 50 Hz

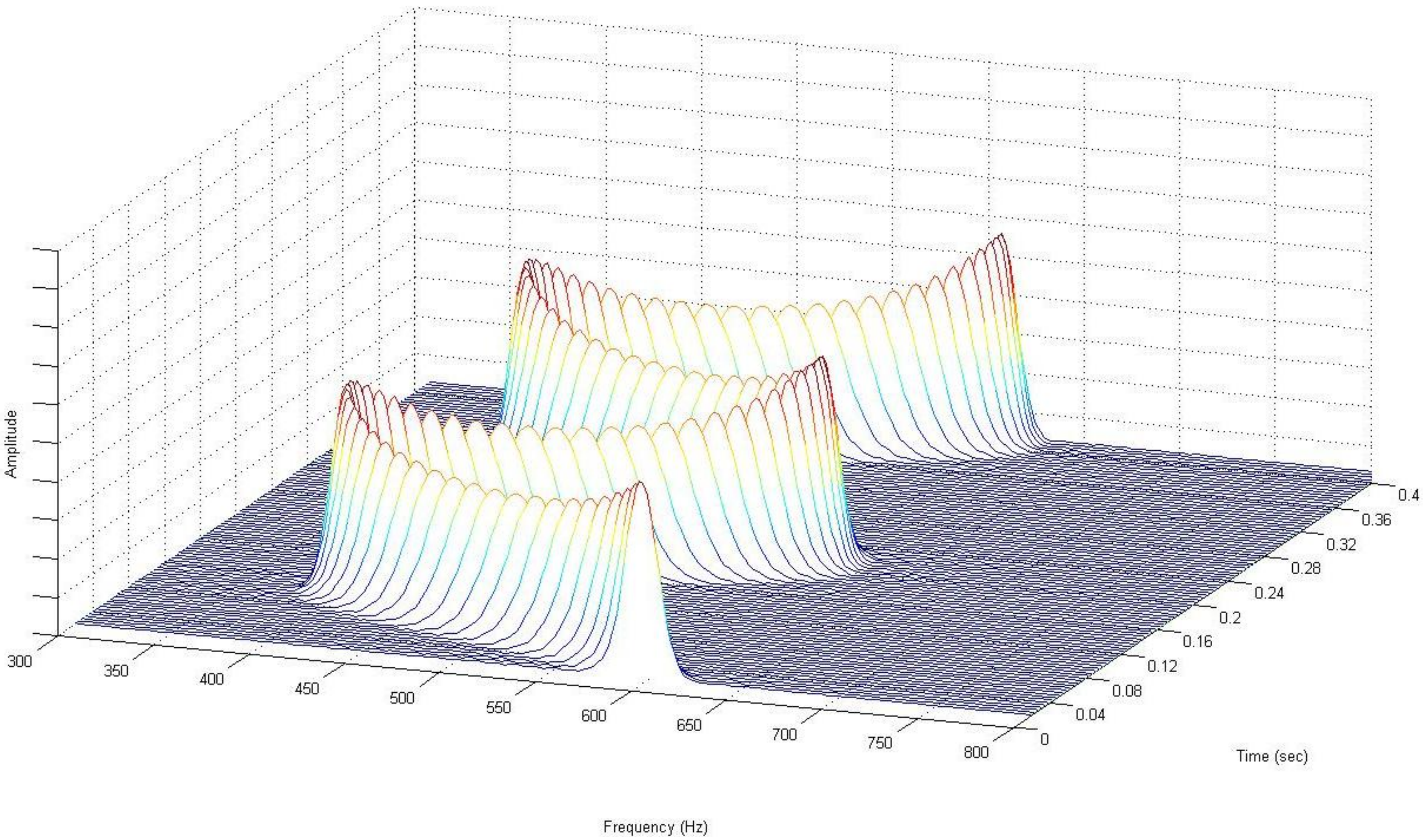

Figure 3: Spectral representation of a frequency-modulated fixed-amplitude tone with CF: 500 Hz, MF: 4 Hz, and Dev: 100 Hz

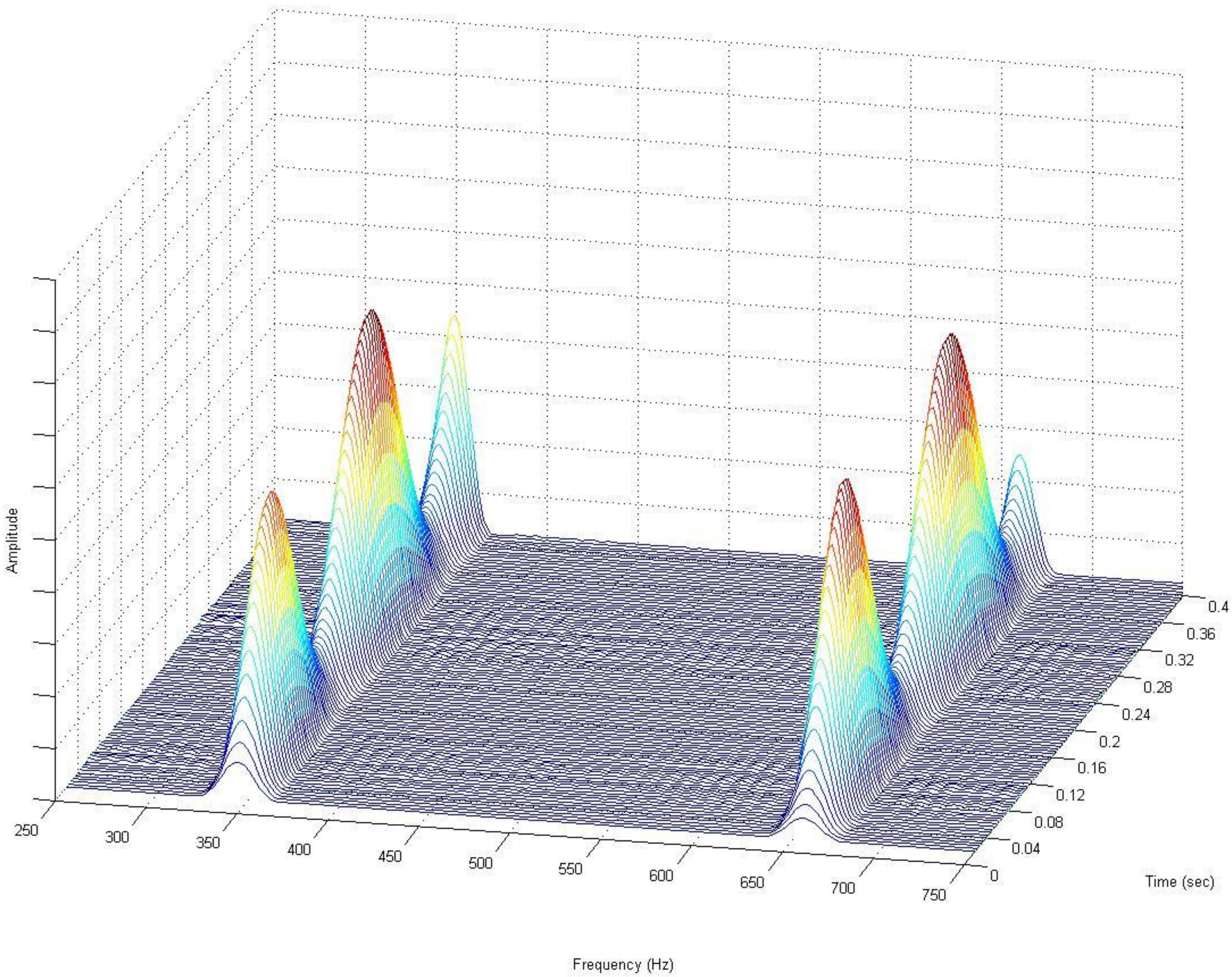

Figure 4: Spectral representation of two fixed-frequency amplitude-modulated tones to create a COG with CF: 500 Hz, MF: 4 Hz, Dev: 50 Hz (45 degrees)

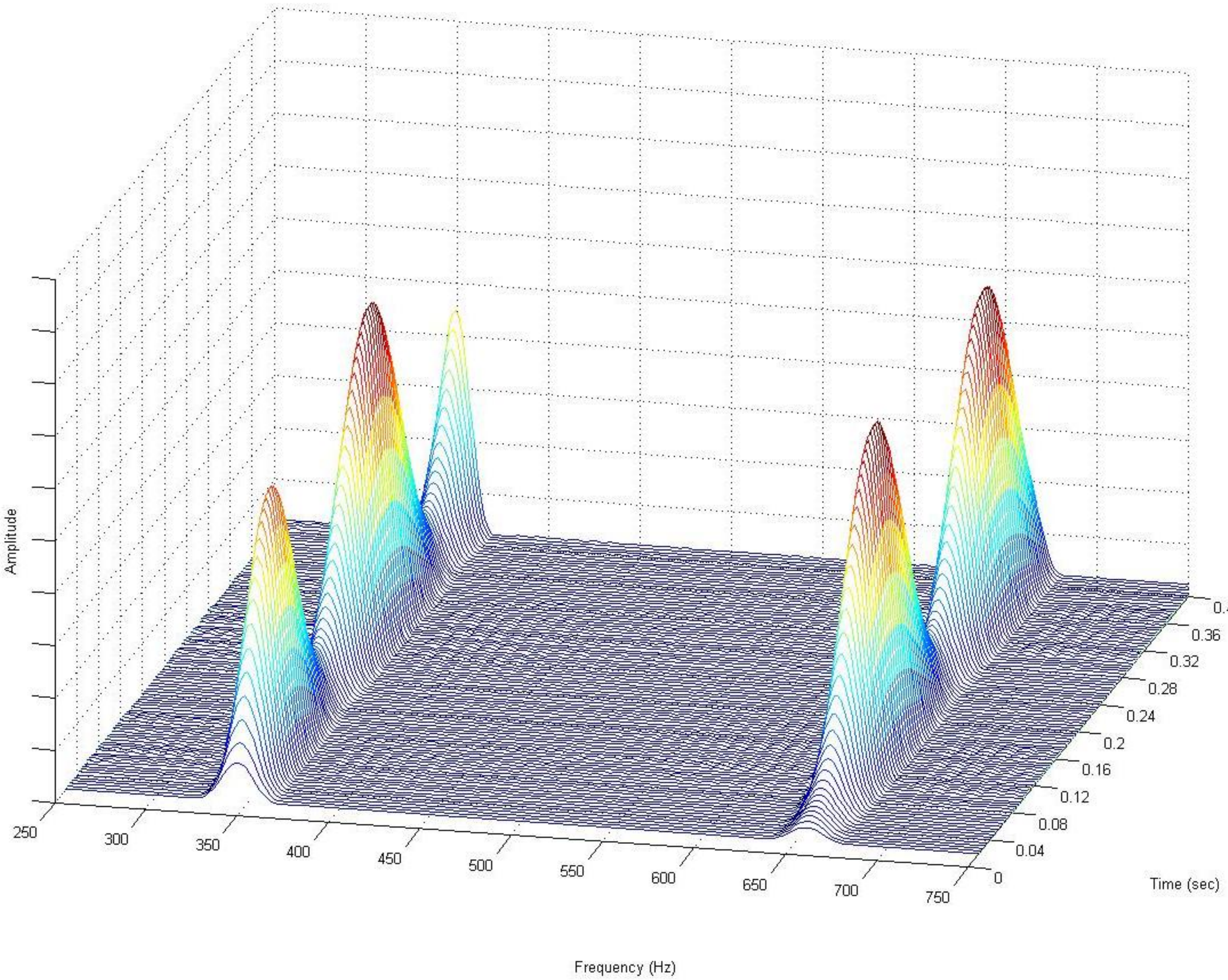

Figure 5: Spectral representation of two fixed-frequency amplitude-modulated tones to create a COG with CF: 500 Hz, MF: 4 Hz, Dev: 100 Hz (150 degrees)

CHAPTER 3

RESULTS

The FM and COG DLs were plotted across MFs, CFs, and Devs to get a better idea about processing. These results are illustrated in Figures 6-14.

FM Results

Part of the research question was “are the COG signals being processed the same way as the FM signals?” To answer this question, it is important to be sure that the listeners in this study produced DL results that agree with the results reported by Ozimek and Sek (1990). The patterns of FM DLs from Ozimek and Sek’s study were beautifully replicated in the current project. The ability to reproduce the same FM results as a previous study provides evidence for concurrent validity of this study.

Figures 6, 7, and 8 display the relationship between DL and MF at each CF. The three bottom (green) plots of each figure represent the FM DLs. Ozimek and Sek found that the FM DLs remain stable across MF so the plots were horizontal. It is easy to see that the FM plots for the current study are horizontal across MF, too. This means that the FM DLs are independent of modulation frequency.

Figure 9, 10, and 11 display the relationship between CF and DL at each MF. The three bottom plots of each figure represent the FM DLs. Ozimek and Sek found that the FM DLs remain stable across CF so the plots were horizontal. The FM plots for the current study are relatively horizontal across CF, too. This means that the FM DLs are independent of center frequency.

Figures 12, 13, and 14 display the relationship between Dev and DLs at each MF. The three bottom plots of each figure represent the FM DLs. Ozimek and Sek found that the FM DLs increase nonlinearly across Dev. This was represented by a positive slope. The FM plots for the current study suggest a positive, but not linear, slope across CF, too. This means that the FM DLs are at least somewhat dependent on deviation.

COG Results

The most self-evident phenomenon in the COG results is that the COG DLs are generally about three times larger than their matching FM DLs. It is also obvious that there is more variability among the COG DLs than the FM DLs. The magnitude differences between FM and COG DLs were not surprising. However, it is their patterns (how they change across CF, MF, and Dev) that reflect processing.

The statistical significance level was set at 0.01 to help offset the small number of subjects, even though no statistical power test was run. A four-factor (stimulus type, CF, MF, and Dev) ANOVA showed that the main effect of stimulus type (FM vs. COG) with one degree of freedom was significant with $p = 0.002$.

Figures 6, 7, and 8 display the relationship between DL and MF at each CF. The three top (red) plots of each figure represent the COG DLs. In figures 6 and 7, the COG DL plots run relatively parallel to the FM DL plots. At CFs of 250 and 500 Hz, the COG DLs are reasonably horizontal so COG DLs seem to be independent of MF. Yet at a CF of 1000 Hz, the COG DL plots all have a positive slope. This provides evidence for the COG being processed differently at 1000 Hz than at the lower frequencies. Both the main effect of MF and the interaction of MF with stimulus type were not significant with $p = 0.062$ and 0.043, respectively.

Figures 9, 10, and 11 display the relationship between DL and CF at each MF. The three top (red) plots of each figure represent the COG DLs. In all three figures, the

COG DL plots, though varied, have a slight, generally positive slope. The COG DL plots are not parallel to the analogous FM DL plots. This means that the COG signals are probably being processed differently from the FM signals across center frequencies. . Both the main effect of CF and the interaction of CF with stimulus type were significant with $p = 0.002$ and 0.004, respectively.

Figures 12, 13, and 14 display the relationship between DL and Dev at each MF. The three top (red) plots of each figure represent the COG DLs. In all three figures, the COG DL plots have positive slopes. Because the FM DL plots also have a positive slope, the COG DL plots are parallel to the analogous FM DL plots. This means that the COG signals are probably being processed similarly to the FM signals across deviations. The main effect of Dev was significant with $p < 0.001$. The interaction of Dev with stimulus type was not significant with $p = 0.302$.

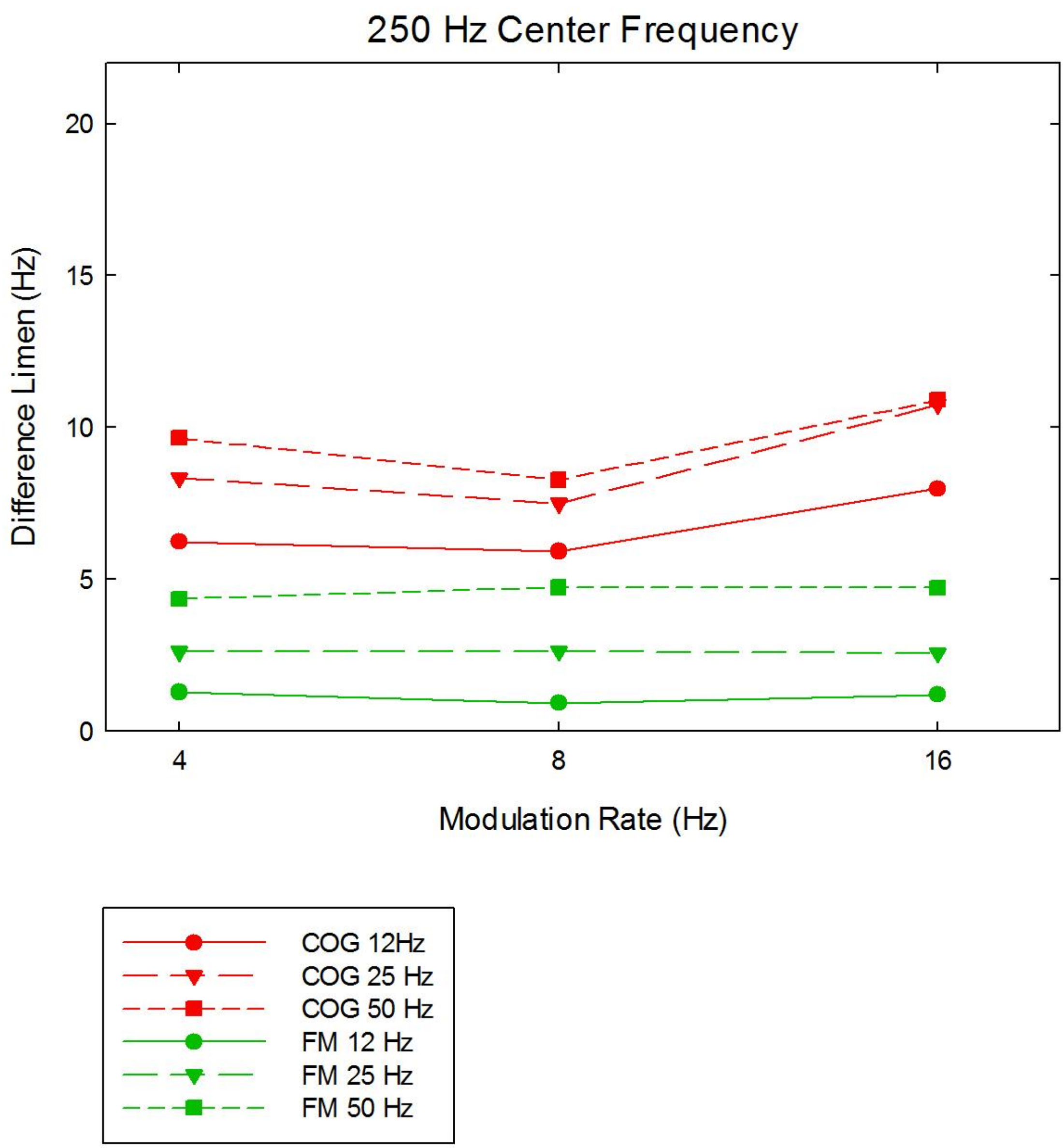

Figure 6: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at CF of 250 Hz. The independent variable is MF; the parameter is the Dev of each reference signal**.**

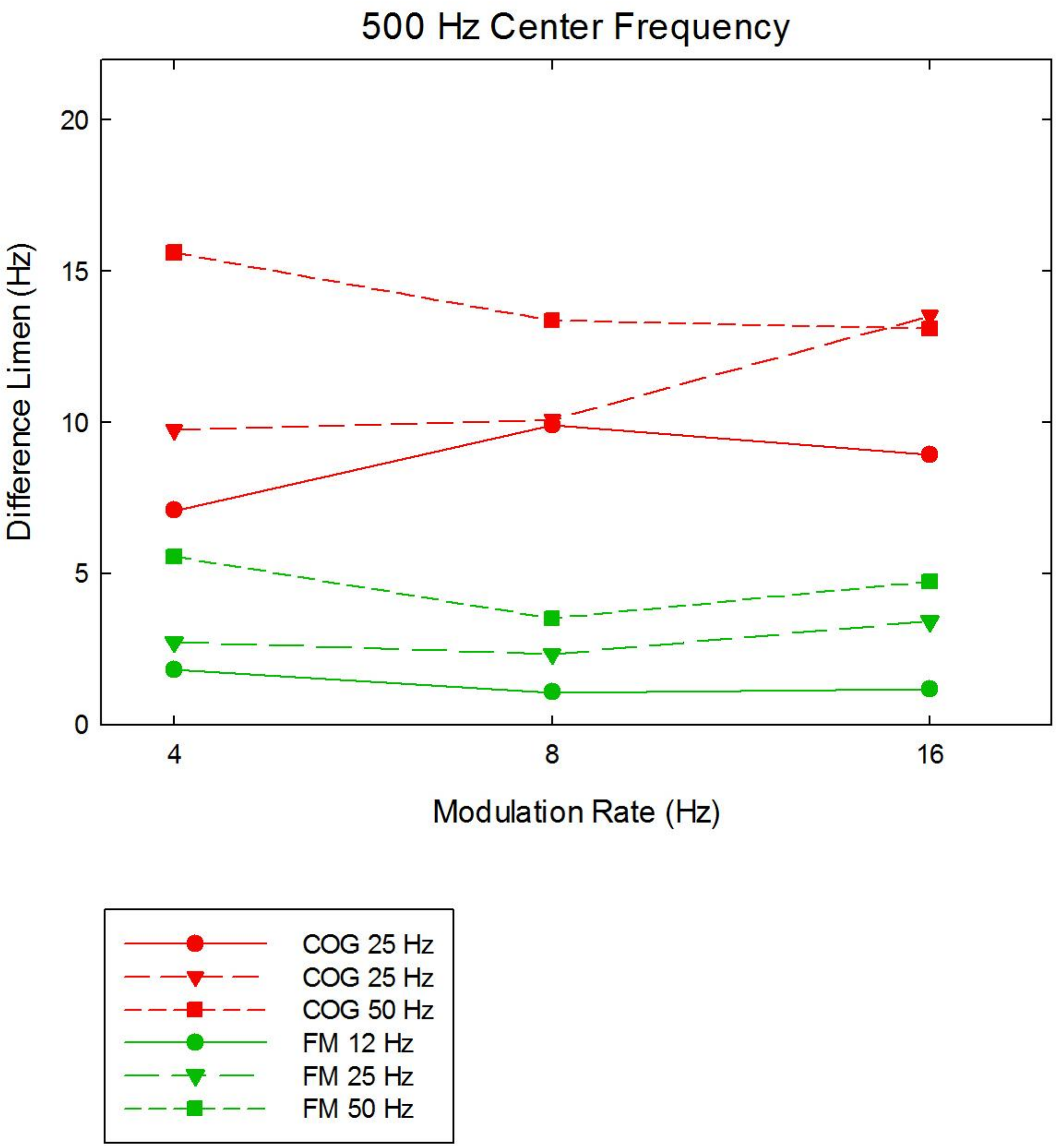

Figure 7: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at CF of 500 Hz. The independent variable is MF; the parameter is the Dev of each reference signal**.**

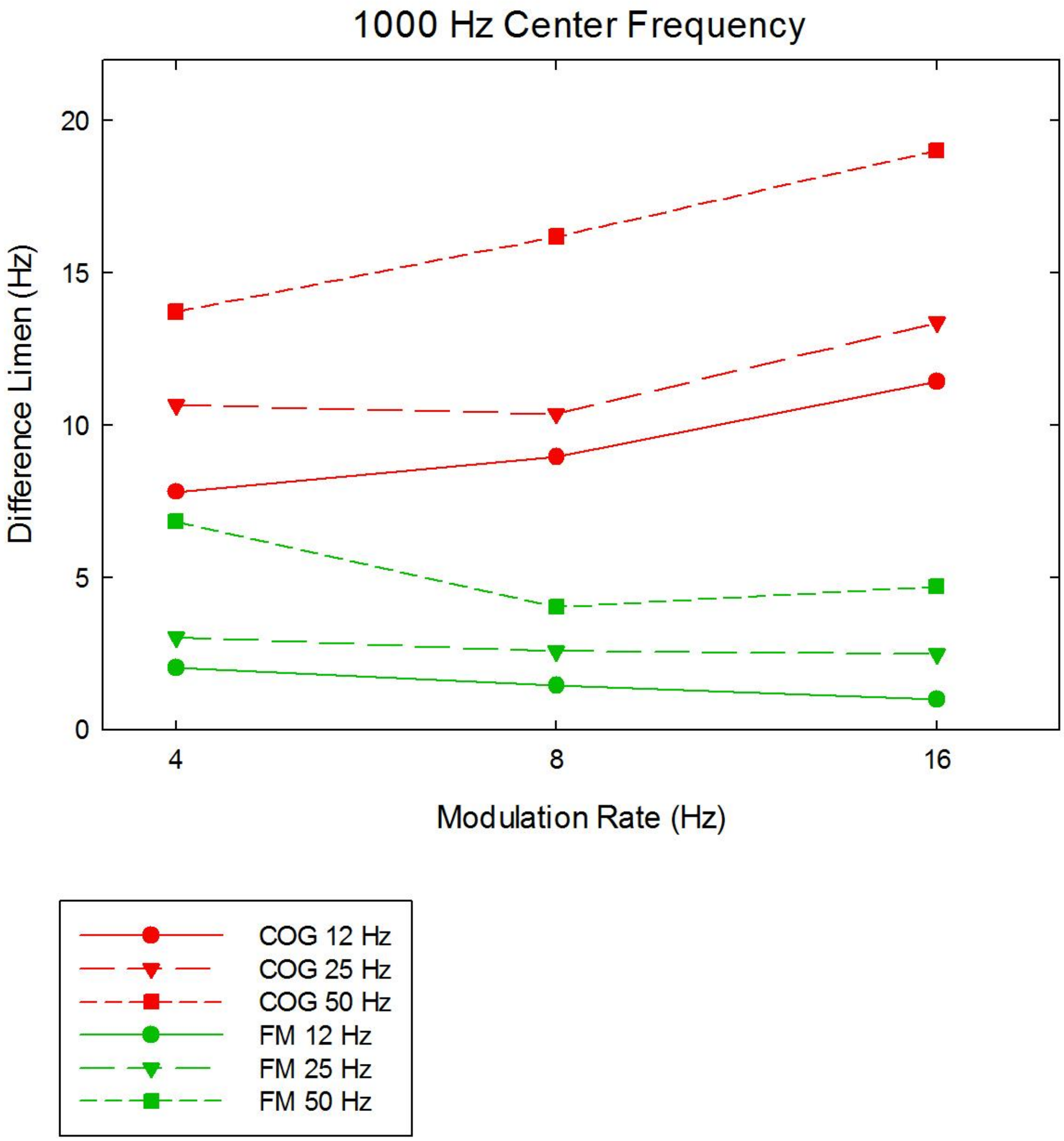

Figure 8: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at CF of 1000 Hz. The independent variable is MF; the parameter is the Dev of each reference signal**.**

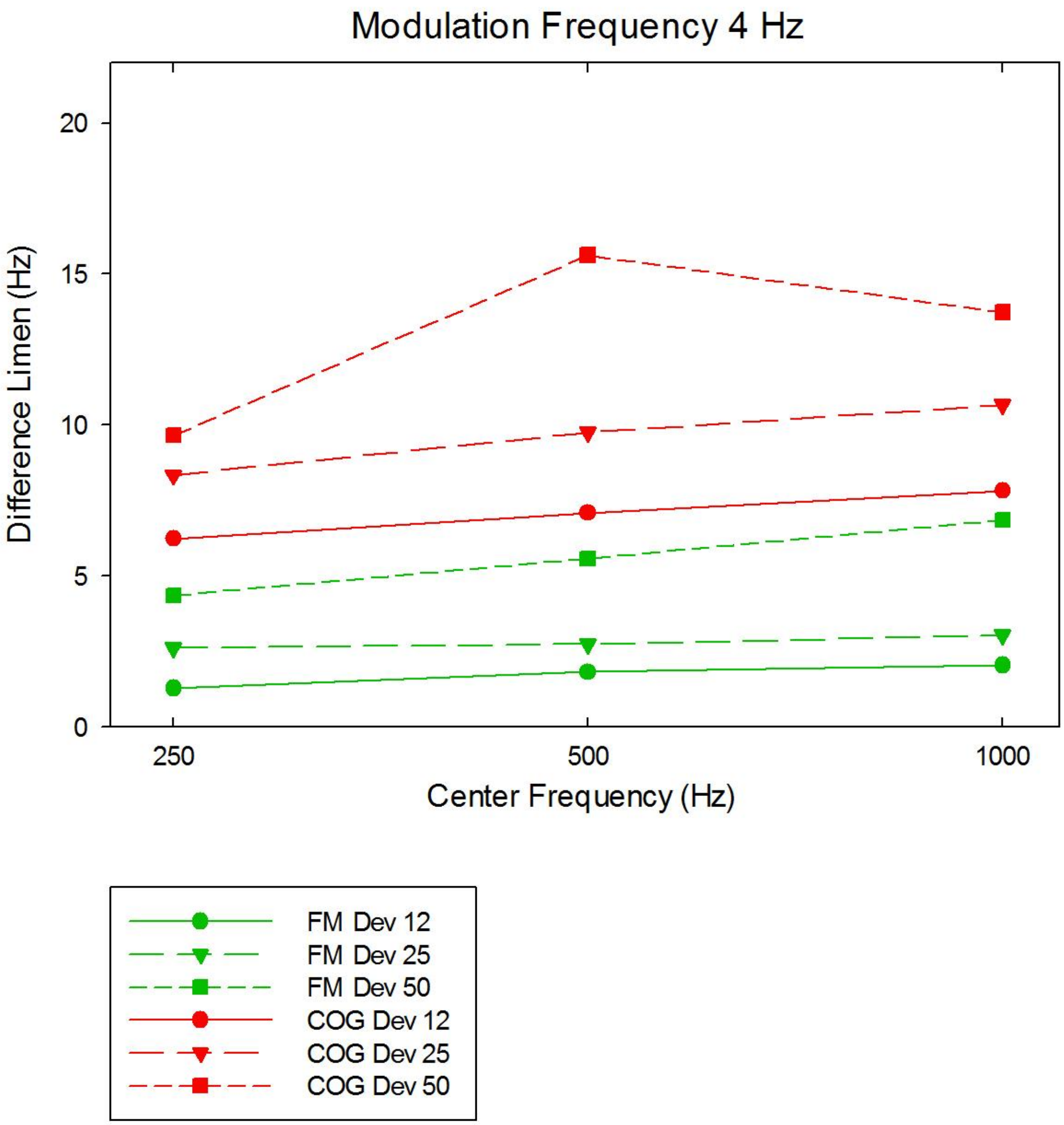

Figure 9: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at MF of 4 Hz. The independent variable is CF; the parameter is the Dev of each reference signal.

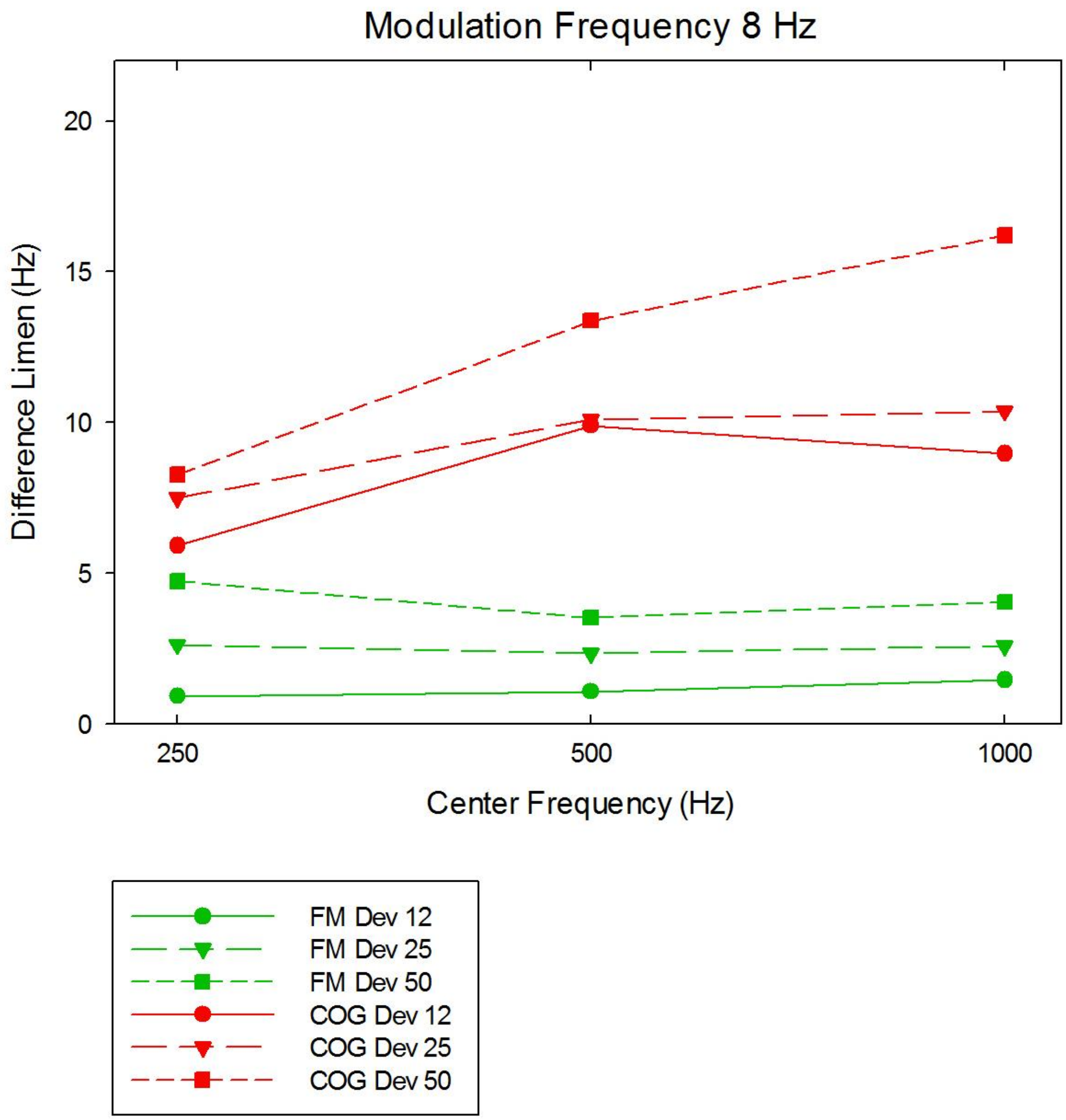

Figure 10: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at MF of 8 Hz. The independent variable is CF; the parameter is the Dev of each reference signal.

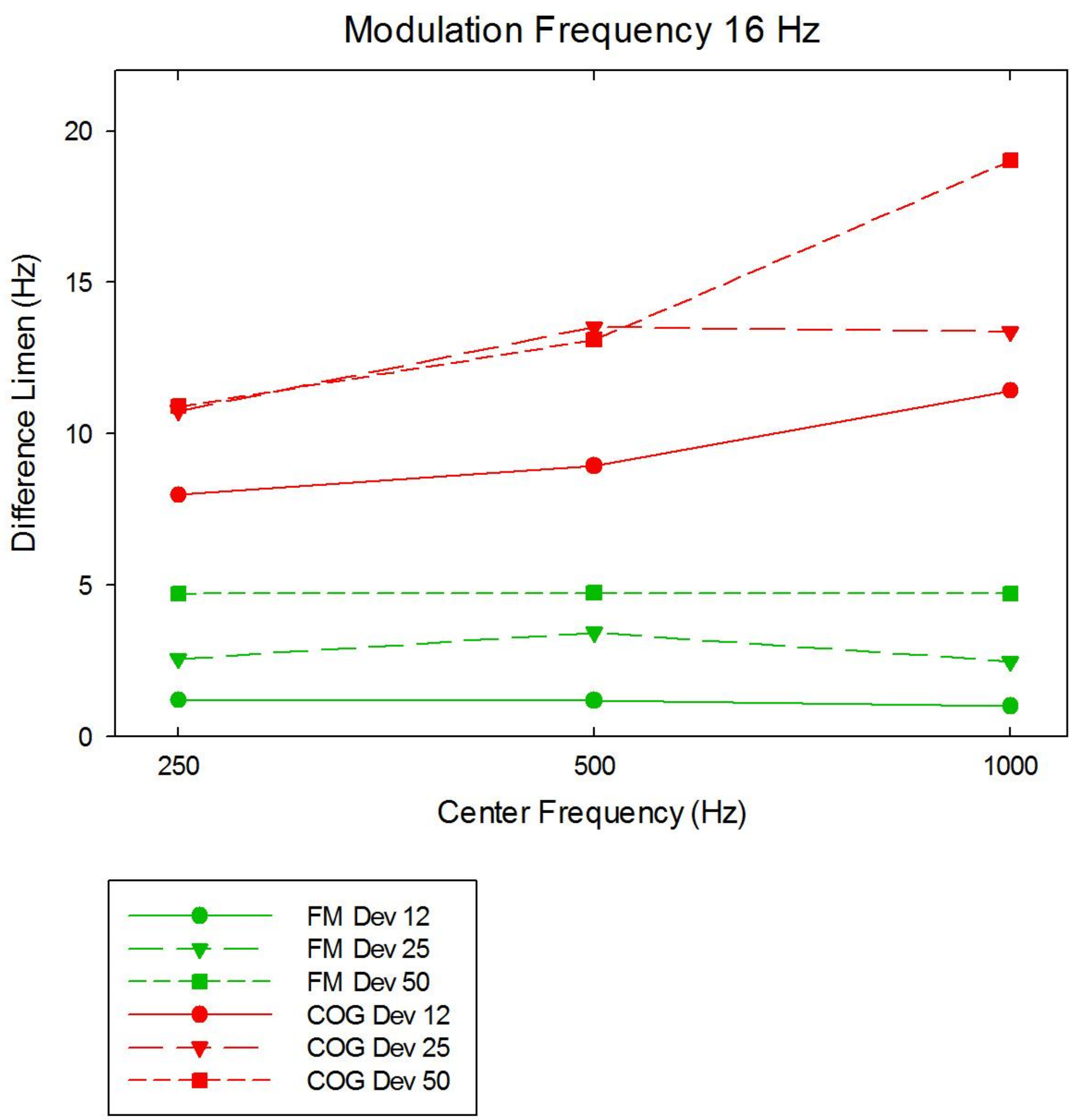

Figure 11: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at MF of 16 Hz. The independent variable is CF; the parameter is the Dev of each reference signal.

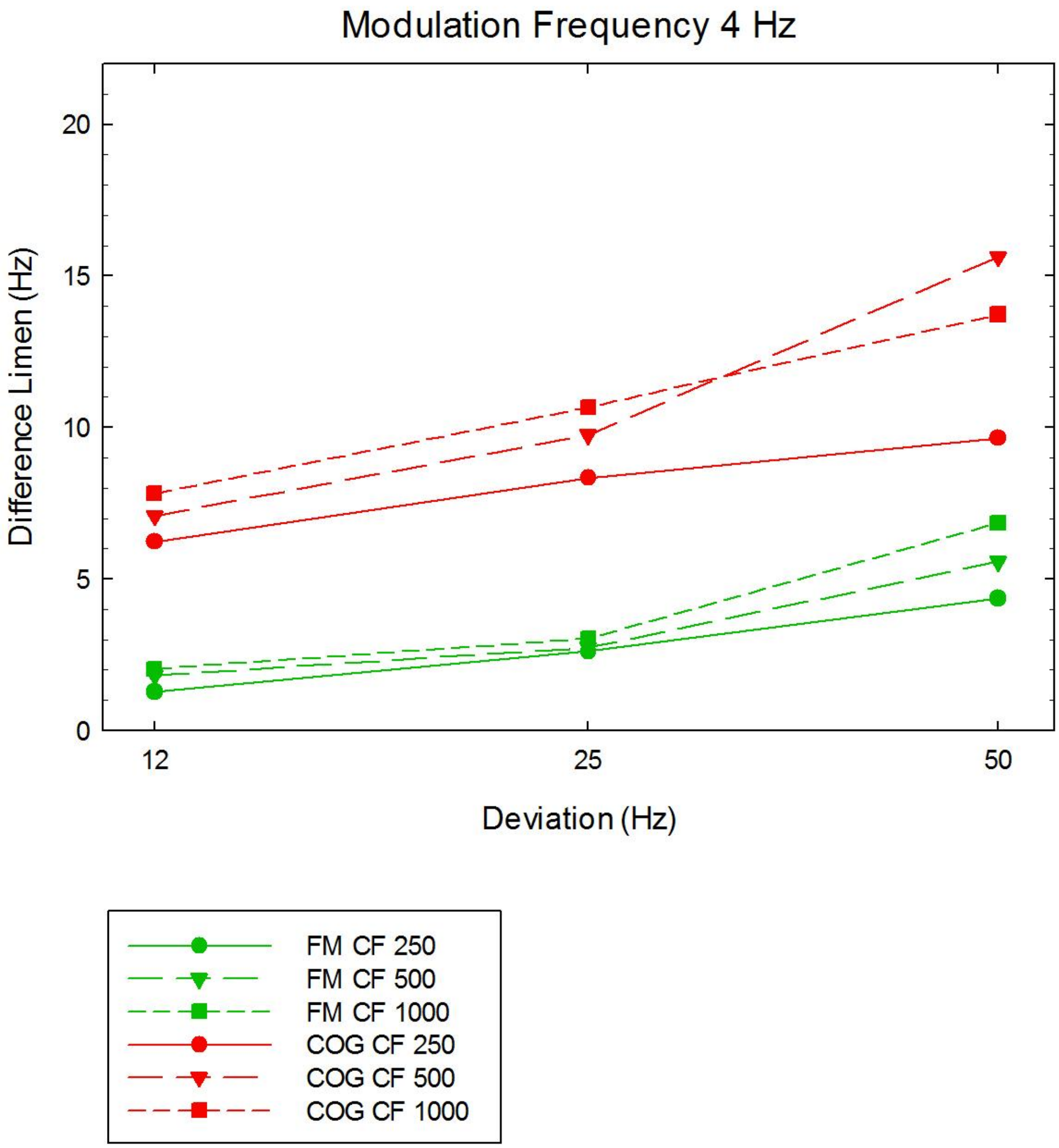

Figure 12: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at MF of 4 Hz. The independent variable is frequency deviation; the parameter is CF.

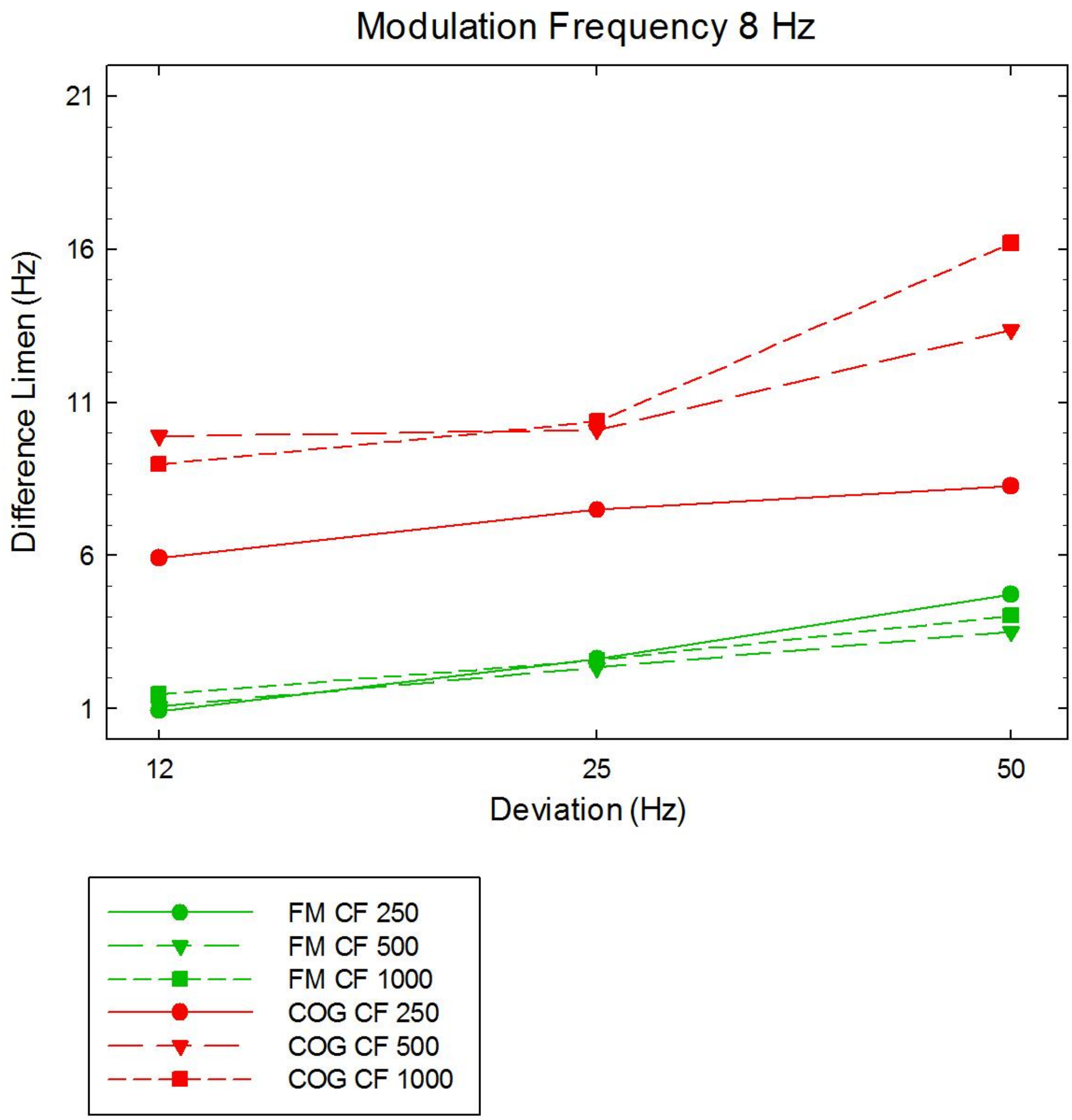

Figure 13: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at MF of 8 Hz. The independent variable is frequency deviation; the parameter is CF.

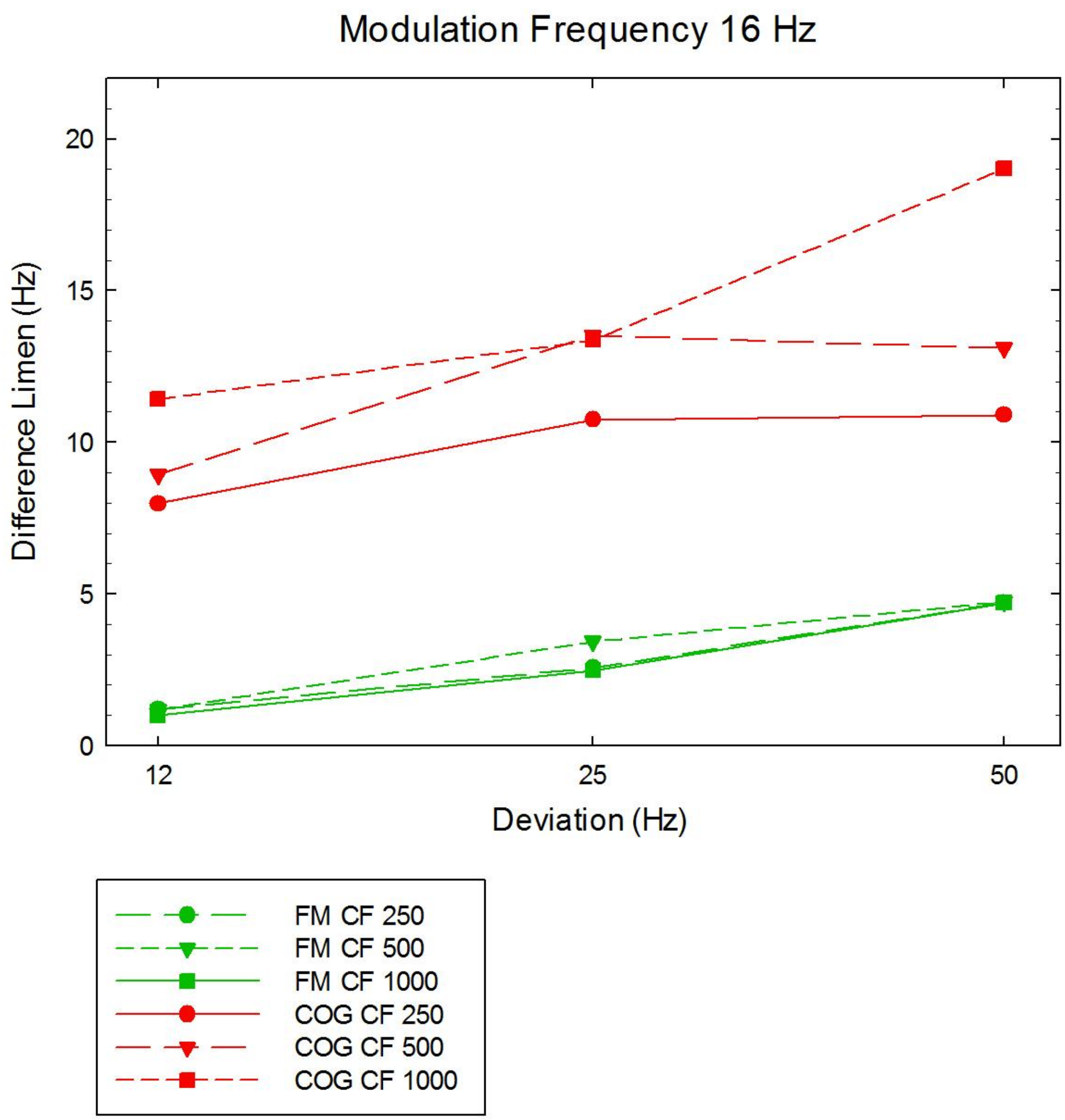

Figure 14: Averaged DLs for frequency deviation in FM (green) and COG (red) signals for the five listeners at MF of 16 Hz. The independent variable is frequency deviation; the parameter is CF.

CHAPTER 4

DISCUSSION

The first part of the research question was: can a listener detect the dynamic COG in the two-tone signals? To answer this directly, yes. This study showed that a listener can track the spectral COGs in the two-tone signals. Supporting evidence for this is that, as a listener practiced the COG task, their DLs improved. This demonstrates that the COG task can be learned and mastered so listeners must have gotten better at detecting the dynamic COG. More evidence for this claim is the consistency of behavior across parameters. Subjects were able to attain 3 DLs within 5 Hz or 5 degrees of each other for each condition which means they were able to replicate their results reliably.

The second part of the research question was: are the COG signals being processed the same way as the FM signals? That is not as easy to answer as the first question. At first glance, an objective observer would look at the noticeable difference between the FM DLs and the COG DLs and assume that the COG signals and the FM signals could not possibly be processed the same way. That objective observer would only be partially correct. In general, the COG DLs were about 3 times greater than their matching FM DLs in magnitude. The main effect, which is the difference in DLs between FM and COG signals, is statistically significant. The differences reflected in the results would not happen by random chance more than 2 times in 1000. Another way of saying this is that the DL of a signal is dependent on stimulus type. A probable explanation for this phenomenon is that the COG task is simply a more difficult task than the FM task. Support for this explanation is threefold: 1) Much more practice time was required for the subjects to master the COG task than the FM task. On average, it took about two hours of practice for each subject to master the FM task. It took the same listeners an average of 12 hours to master the COG task. 2) FM DLs were easily attained at a deviation of 6 Hz, but COG DLs were unachievable at the same deviation. For the COG task at a Dev of 6 Hz, listeners were unable to attain 3 trials close enough in magnitude to be counted as a reliable DL. 3) Anecdotal reports from listeners provide support for the explanation. Listeners simply told us that the COG task was more difficult than the FM task. Furthermore, the actual numerical results show that there is a significant difference between the COG DLs and the FM DLs. Yet the numbers themselves do not necessarily reflect processing. It is the patterns of DLs across CFs, MFs, and Devs that reflect processing. To analyze these patterns, we looked at each parameter and the two-way interactions between stimulus type and CF, MF, and Dev.

The main effect of MF was not significant. Another way of saying this is that FM and COG DLs are independent of MF. The interaction between stimulus type and MF was not significant either. Another way of saying this is that COG DLs are changing in the same way as the FM DLS across MF. This compilation of data supports the hypothesis that COG signals are being processed the same way as FM signals across modulation frequency.

The main effect of CF was significant. Another way of saying this is that FM and COG DLs are somewhat dependent on CF. The interaction between stimulus type and CF was significant, as well. Another way of saying this is that COG DLs are changing differently than the FM DLS across MF. This compilation of data does not support the hypothesis that COG signals are being processed the same way as FM signals across center frequency.

The main effect of Dev was definitely significant. Another way of saying this is that FM and COG DLs are very dependent on Dev. The interaction between stimulus type and MF was not significant. Another way of saying this is that COG DLs are changing in the same way as the FM DLS across Dev. This compilation of data supports the hypothesis that COG signals are being processed the same way as FM signals across deviation.

To answer the second part of the research question succinctly: The COG signals appear to be processed the same way as the FM signals with some differences. The patterns of DLs across center frequency are different between FM and COG signals so they might be processed differently with respect to center frequency. Specifically, the COG DLs for 1000 Hz differ from FM DLs with respect to MF. Nevertheless, the patterns of DLs across modulation frequency and deviation are same for FM and COG signals. This indicates that they are being processed the same way with respect to modulation frequency and deviation. The results support the idea that a central auditory processing mechanism (probably located between the VIIIth cranial nerve and the auditory cortex) may exist for tracking the changes in the spectral COG for complex signals such as speech and music.

In the future, the experimental results of this study will be used to create a computational model of the COG effect that can be run through the Ohio Supercomputer Center. This will simulate thousands of channels at the same time so we can better understand the physiology of the central auditory system. Another possibility for future study on this topic is looking into the listener effort of the COG signals. We consider the COG task to be more difficult than the FM task, but we would like to see if that is empirically true. It could also set the foundation for how to measure listener effort.

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Soli Deo Gloria.

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